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SINGLE-PHASE RAILWAYS.

BY W. A. BLANCK.

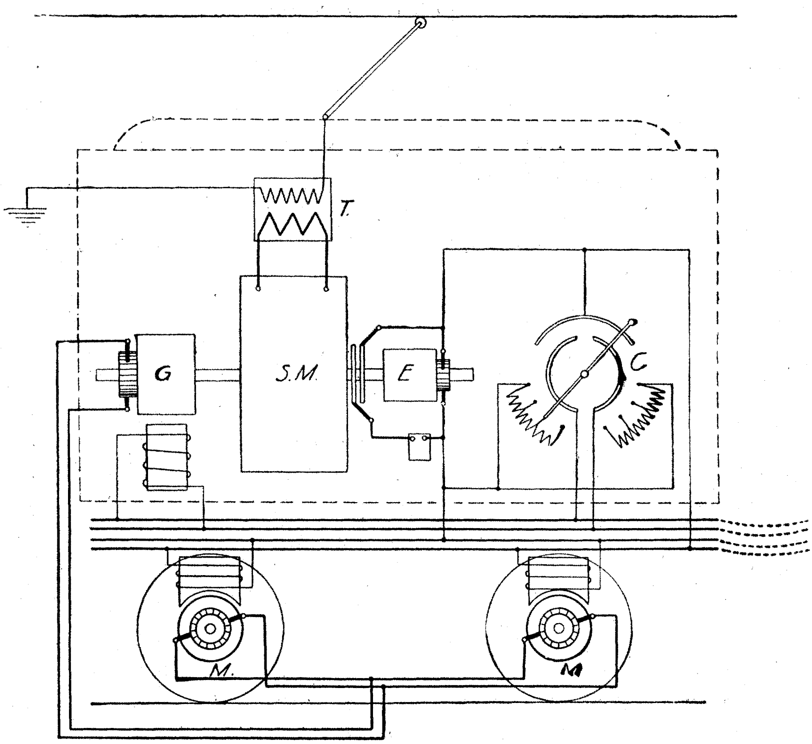
In perhaps no line of electrical industry has there been greater activity than in that of interurban railway construction. At the present time in the United States, particularly in the Central States, this development has reached a magnitude entirely beyond the expectations of the most sanguine of a decade since. In fact this development has gone so far that in some sections most of the best propositions are already exploited; however, there are still a great many, which, while of doubtful value with the present direct-current system—involving the use of synchronous converter sub-stations and low trolley pressure—would be very profitable if a system could be developed that would materially reduce the cost. For some time the perfecting of the single-phase motor has been suggested as the solution of this problem, since the application of this motor to electric traction means a great reduction in the cost of the transmission system. The present activity in the evolution of the single-phase railway motor gives added interest to the problem of developing and perfecting all the other details of the single-phase system.

The subjects to be considered in this paper are: 1, The fundamental characteristics of the various single-phase railway motors; 2, Certain details of line construction; and 3, The comparative cost of installing typical power-houses, sub-stations in power-houses, transmission lines, sub-stations along the road, trolley lines and feeders, and bonding of rails for a 60-mile, single-track interurban railway on direct-current and alternating-current systems.

The first problem to be solved is the development of a single-phase alternating-current motor that will operate satisfactorily under the conditions imposed by railway service. The importance of this problem was early recognized and its solution has been sought by many of the ablest engineers both here and abroad.

The attention given the single-phase system by the technical press has brought it prominently before engineers, but a short resumé of the present state of the art may not be out of place.

SYNCHRONOUS MOTOR



WARD LEONARD

FIG. 1.

THE SYNCHRONOUS MOTOR.

The synchronous motor requires a separately-excited field, has no starting torque, and cannot be run at variable speed, therefore its direct application to railway traction is impossible. It has been proposed by Ward Leonard to use the synchronous motor in combination with a direct-current generator, to furnish direct-current to standard motors. This idea shown in Fig. 1, which is lettered to be self-explanatory.

THE INDUCTION MOTOR.

In respect to starting and speed-control the induction motor shows the same peculiarities as the synchronous motor; to overcome these peculiarities, Bion J. Arnold proposes a suitable combination of an induction motor with a mechanical energy-storage contrivance, this contrivance consisting of an air-compressor and tank. The various members of this combination are indicated in Fig. 2. In this system both parts of the motor are

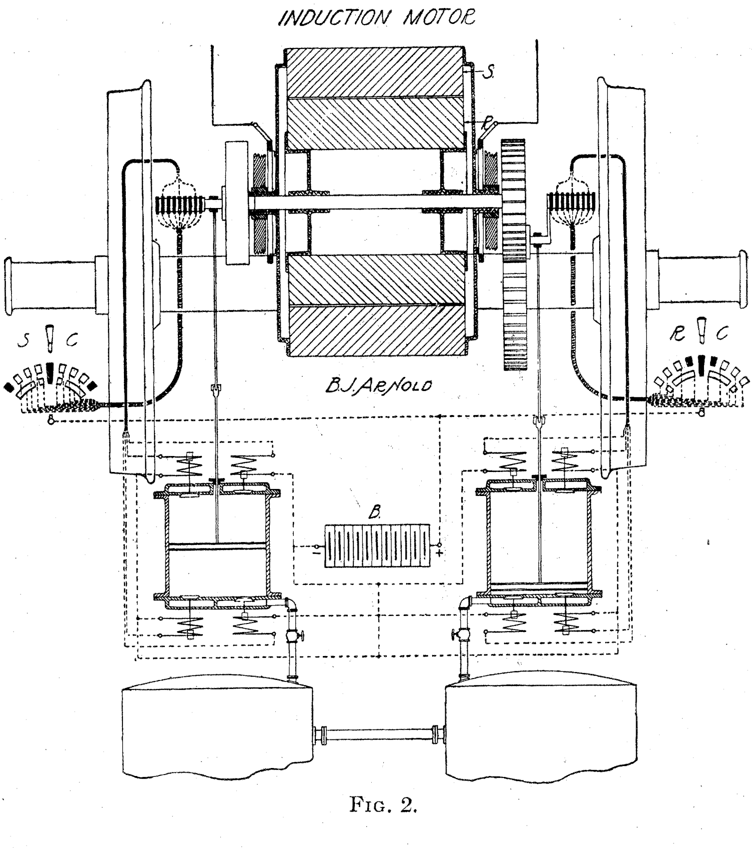


FIG. 2.

free to rotate, and they maintain a constant relative speed. The rotor is geared to the axle and also connected to one air-cylinder. The stator is connected to a second air-cylinder, in which, when the car is running at less than full speed, air is compressed. When the car is at full speed the stator is at rest and there is no compression. By admitting air to this cylinder and rotating the stator in the same direction as the rotor the car can be run at more than synchronous speed.

This combination, with the induction motor continually running, makes it possible to store energy when the car is coasting or stopped, and to use this energy when the car is accelerated. Further, this system allows the operation of the car by compressed air for a limited time, should it be desirable to run without overhead conductor.

THE SERIES MOTOR.

The alternating-current series motor, as proposed by Lamme and Finzi and manufactured by the Westinghouse Electric & Mfg. Company, possesess the characteristics of a direct-current series motor; it is, therefore, directly applicable to railway work.

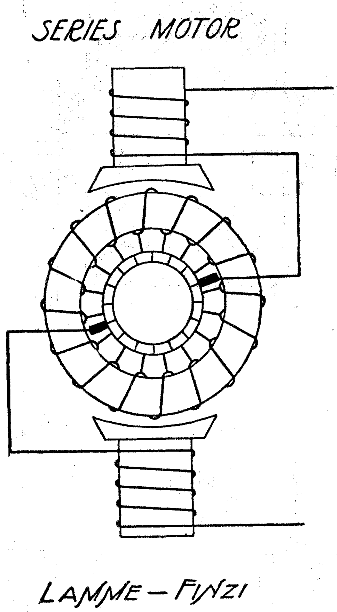


FIG. 3.

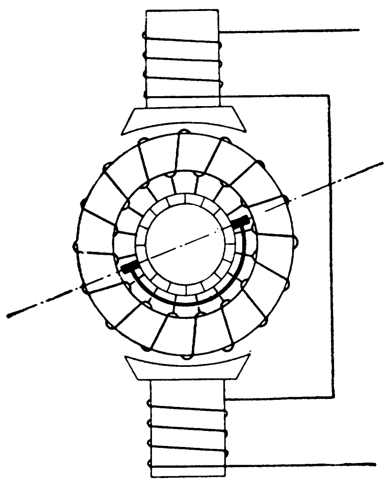
As shown in Fig. 3, the current passes in series through the field and armature. The armature is similar to the ordinary direct-current drum-type armature with commutator. As the direction of rotation in the direct-current series motor is not dependent on the direction of the current, it is evident that the motor will operate with alternating as well as with direct current.

Since the series commutator motor cannot be operated at high-pressure, it is necessary to use a step-down transformer in connection with a high-pressure trolley, thus increasing the weight of the car equipment.

THE REPULSION INDUCTION MOTOR.

The repulsion induction motor developed by Steinmetz and Schüler and manufactured by the General Electric Company, shows in general the same characteristics as the straight-seires motor; it can be operated directly from the high-pressure trolley, since, as indicated in Fig. 4, the armature is independent of the field. The current is induced in the armature by transformer action and can be of any desired pressure. The brushes are short-circuited and placed at an angle to give the best running conditions.

REPULSION INDUCTION MOTOR



STEINMETZ—SCHÜLER

FIG. 4.

THE REPULSION SERIES MOTOR.

The repulsion series motor developed by Winter-Eichberg and built by the Union Electric Company, Berlin, Germany, is similar to the repulsion induction motor with the addition of a second set of brushes, displaced 90° from the short-circuited brushes, as shown in Fig. 5. Through these brushes current is supplied by a series transformer; this is done for the purpose of decreasing the sparking at less than synchronous speed, and securing the important additional advantage of raising the power-factor nearly to unity.

CONTROLLERS.

In general, the operation of the last three motor systems is effected by master controllers operated to get the desired combinations. To obtain the voltage variation necessary for speed-control, induction regulators are used in all three cases, thus avoiding the losses consequent to the rheostatic control of the direct-current system.

CAR WIRING.

To protect passengers and crew from the high pressure used in this system, it is necessary that the wiring should be done in

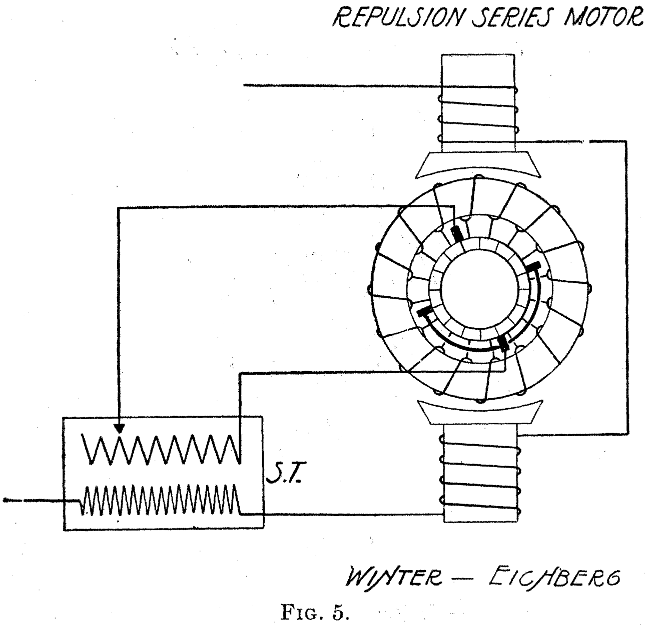


FIG. 5.

metallic conduit; this should be connected to the trucks so that any defect in the insulation of the circuit will result in the tripping of the automatic circuit-breaker in the car. Moreover, it will be necessary to insulate the steps and hand-rails to guard the passengers from shocks, which might occur during wet weather or from a car standing on a dirty rail.

TROLLEY BOW.

With the high-pressure working conductor it is necessary to provide against any possible short-circuiting of the trolley and its suspensions. On account of the serious results which would follow the slipping of the trolley pole so common in the present system, a suitable bow must be used instead. This trolley bow is mounted on a well-insulated platform on the roof of the car;

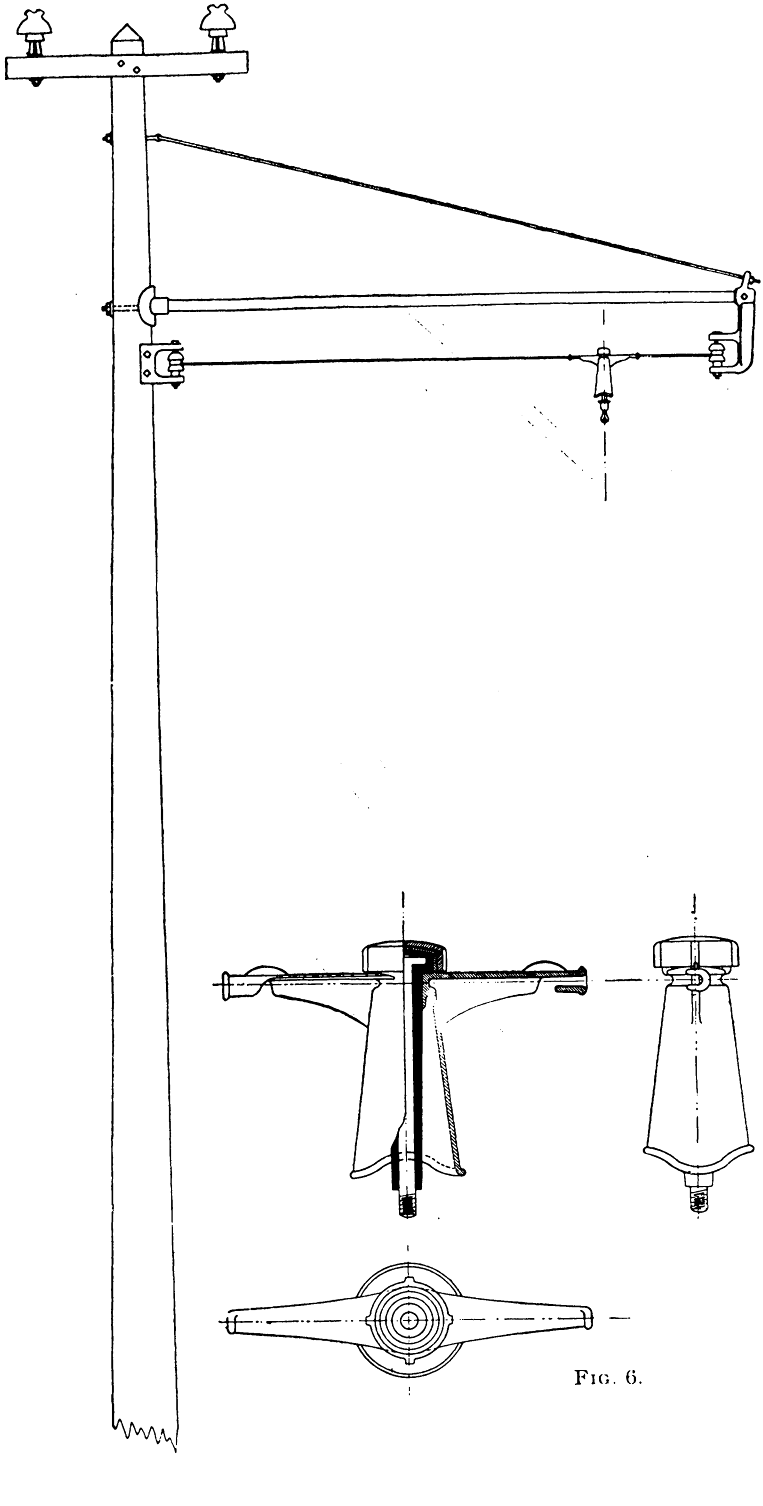


Fig. 6.

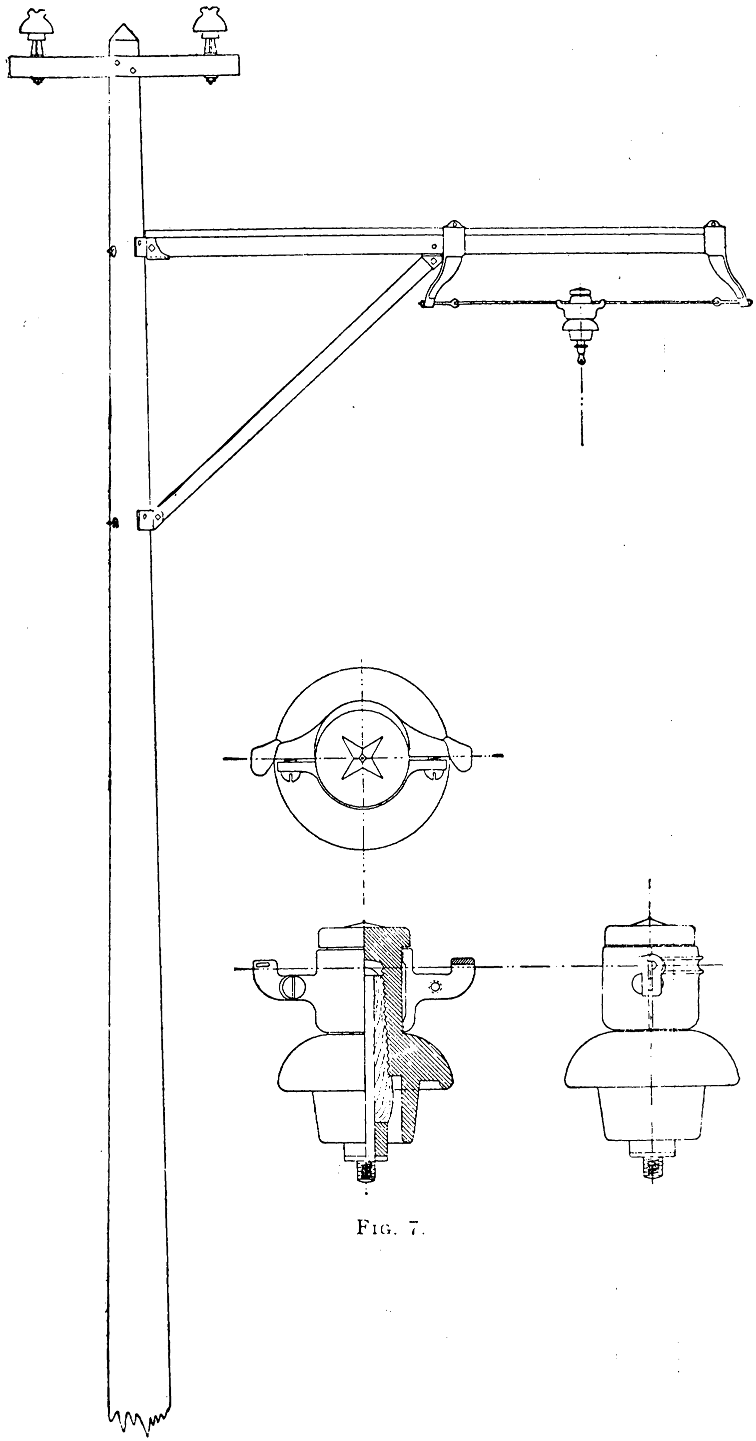


FIG. 7.

this platform also supports the springs necessary to maintain the requisite pressure between the bow and the trolley wire. A small air-cylinder, mounted on the same platform, operated by compressed air from the brake system, should be so connected as to lay the bow flat on the roof of the car, in case the necessity arises to disconnect temporarily the bow from the trolley. The contact part of the bow can be made either of soft copper or aluminum. The necessary lubrication is accomplished by grease applied in a slot extending the length of the bow. The bow should be of such length that no manipulating will be necessary when reversing the car.

The trolley bow in use on the Valtelina road in Northern Italy with a working pressure of 3000 volts, consists of copper cylinders rolling in insulated ball-bearings. Brushes take the current from these revolving cylinders to the steel tubes carrying the contact-piece.

Trolley-Line Construction.

In order to protect life and property, great care must be used in constructing the high-pressure trolley line. There is a prevailing idea that high-pressure trolleys are dangerous, and it is said that this condition will retard the development of alternating-current railways operated over public property; but there is no reason why these trolleys should not be made as safe as the high-pressure distributing systems of lighting companies, now so common on public property.

It is important to provide a hanger that will readily withstand the working pressure of the system, and one that can be easily replaced in case of mechanical or electrical defects. Fig. 6 shows a trolley-line construction with hangers similar to that used on the Valtelina railway. The bolt carrying the trolley-clamp is surrounded by an insulating compound, called ambroine, and set into a malleable iron bell provided with clamp-arms to secure it to the span-wire. A cast-iron cap-screw holds the insulated bolt firmly in place.

Another construction used on the Lansing, St. Johns & St. Louis Railway, in Michigan, is shown in Fig. 7. The hanger consists of a special high-pressure glass insulator fastened to the span wire in the usual way. The working conductor is carried by an iron pin inserted in a wooden sleeve, on which is turned a thread to fit the glass of the insulator. A thin lead bushing allows the insulator to be firmly clamped by the malleable-iron supports, thus preventing the hanger from jarring loose.

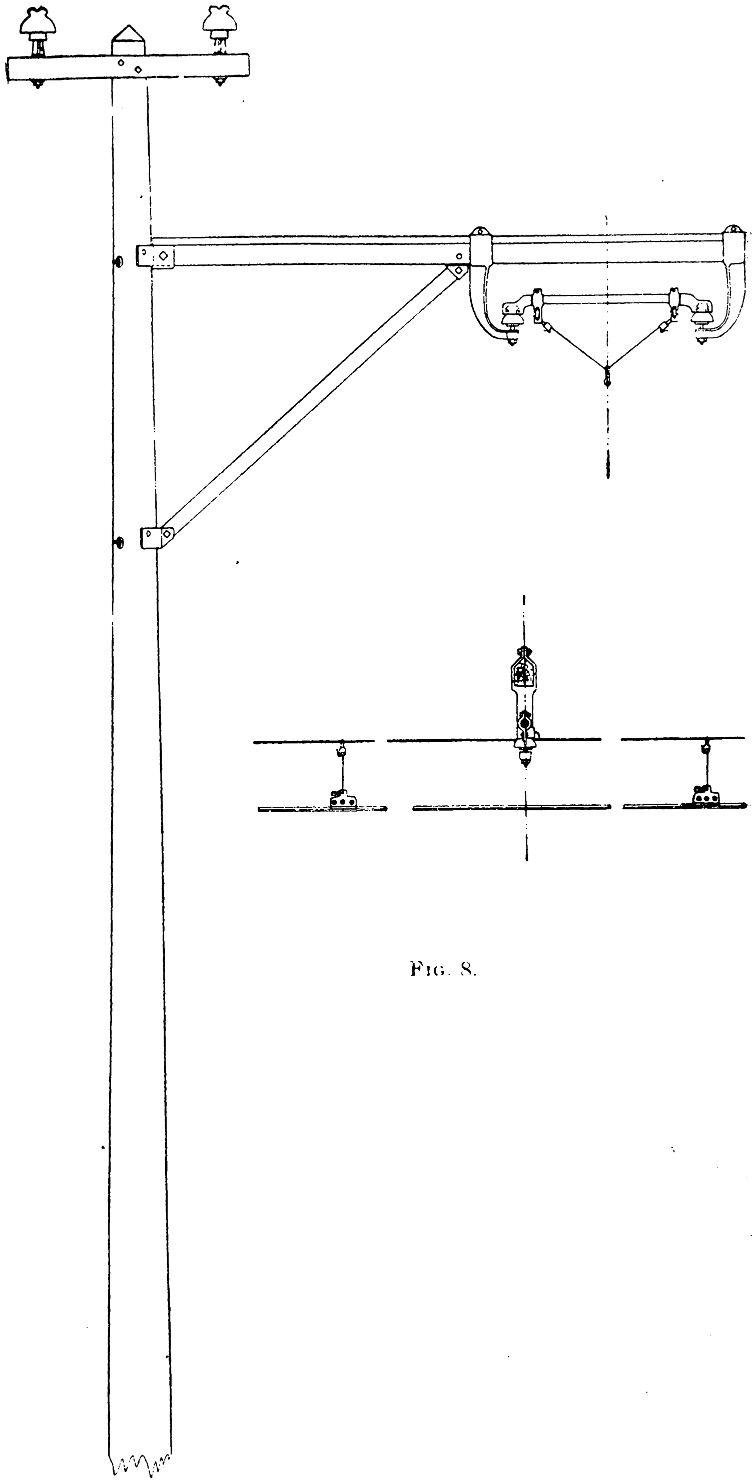


Fig. 8.

If the road operates on a public highway, special precautions should be taken to avoid accident. One solution is shown in Fig. 8; in this the working conductor is suspended at intervals of about ten feet from two steel wires. In case of a mechanical break in the trolley wire it is evident that the end cannot reach the ground or injure passers-by. It might be noted in passing that this construction increases the carrying capacity of the trolley with but slightly greater investment. A construction somewhat similar to this is in use on the single-phase railway near Berlin.

In regard to returning current through the rails, it may be said that with the proposed frequency of 25 cycles per second and the small current required with the higher pressure, this loss will be even smaller than in direct-current railway work, so that for normal interurban service it will be sufficient to bond only one rail. This has the advantage, greatly to be desired in many cases, of leaving the other rail free for the purpose of block signals. Furthermore, the evils of electrolysis are completely avoided with the alternating-current system.

In order to consider more in detail the relative merits of the alternating-current and direct-current systems of distribution, parallel computations and diagrams may be made for the case of a 60-mile, single track, interurban road. We shall assume the power-house to be located at the centre of the line and to contain one sub-station, and that four sub-stations are located at equal intervals on the line, as shown in Fig. 9. Although the alternating-current system will not require sub-stations at as frequent intervals as in the direct-current system, they are retained on account of the advantage derived from sectionalizing the line, and the better distribution of power due to the larger number of feeding points.

The schedule proposed requires five local cars having one-hour headway; one express-car, making the round trip in three hours, and one freight- and baggage-car making the trip between the two terminals in about eight hours.

The average power required by the various cars in kilowatts will be as follows:

	Weight in tons.	Schedule speed in miles per hour.	Watt-hours per ton-mile.	Kilowatt-hours per trip.	Average power in kilowatts
Local-car..........	30	25	80	144	60
Express-car........	35	42.8	110	231	165
Freight-car........	30	12	70	126	25

With the schedule outlined above, the average load on all five sub-stations will be about 500 kw., or 100 kw. per sub-station, while the maximum load per sub-station under certain conditions

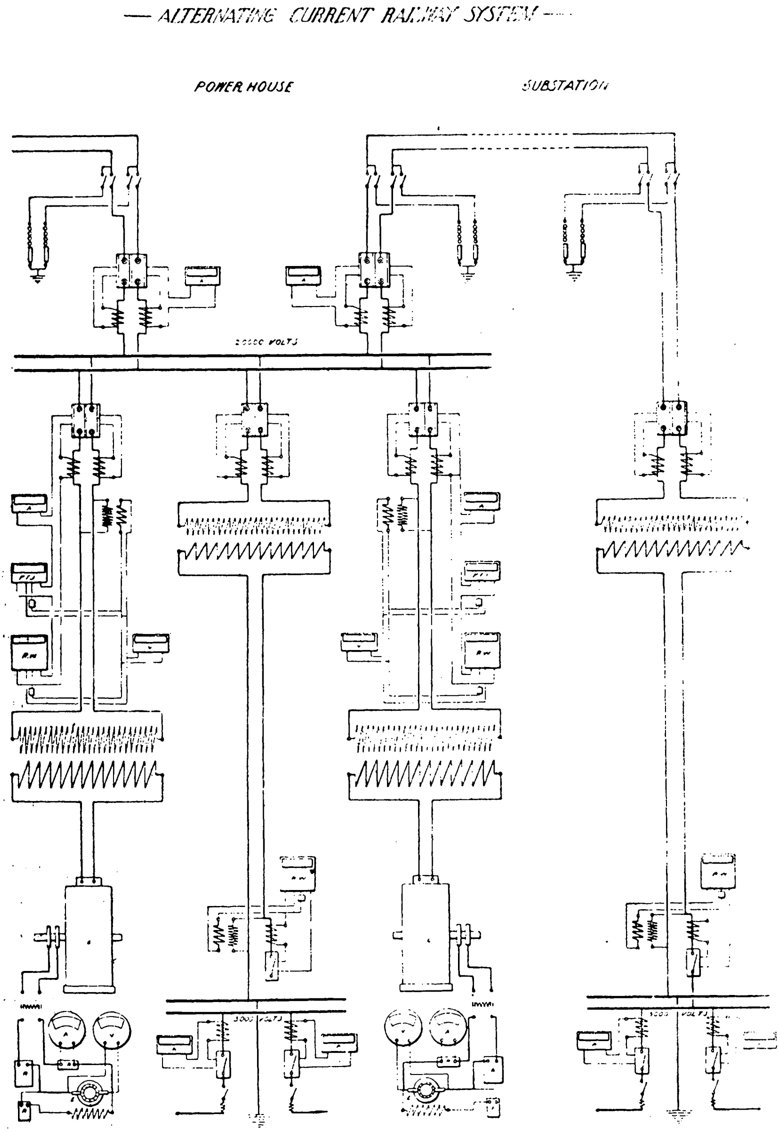


FIG. 9.

is 450 kw., for instance, when the express-car is starting and two locals are running in one section. With a proper momentary overload allowance this assumed condition will require one

300-kw. synchronous converter per sub-station in the direct-current system. In the alternating-current system, however, a static transformer of 200-kw. capacity per sub-station will be ample. The maximum load at the power-house will be 800 kw. and two 400-kw. units will suffice, if for the purpose of this comparative study no reserve capacity be provided either in power-house or sub-stations.

Some idea of the relative simplicity of the transmission systems in the two cases may be obtained from a consideration of the accompanying wiring diagram, Fig. 10, showing the apparatus and connections required in each case. In both cases step-up transformers raise the total generator output to the high transmission pressure, and a step-down transformer set is placed in the power-house. Although the power-house sub-station could take its supply directly from the generators, it is preferred to use one general form for all sub-stations, thus avoiding special switching arrangements. For the three-phase transmission lines of the direct-current railway system, three No. 6 wires are assumed, and for the single-phase transmission line two No. 4 wires, costing respectively $10 000 and $11 500.

The proportions of the distributing-system have been calculated for the following conditions: for the direct-current system it is assumed that the maximum drop in line pressure in the case of a car starting at its maximum distance from sub-stations is approximately 200 volts, or about 30%. This condition can be obtained by installing two No. 000 trolley wires and No. 0000 feeder capacity between sub-stations, and 500 000 circular mils feeder for the stub-ends. The cost of the copper under these conditions will be about $95 000.

For the alternating-current system the size of the trolley wire has been determined from mechanical rather than from electrical considerations. A No. 00 grooved trolley wire has been assumed installed throughout the length of the line, since for this class of service it is not practicable to use smaller sizes. The cost of the copper in this case will be $21 500.

In determining the drop for this system, 80% power-factor is assumed. It will be noted that the maximum drop under the same conditions as above mentioned will be 190 volts between sub-station, or 6.25%, and 380 volts on stub ends, or 12.5%. This shows a considerable advantage in favor of the alternating-current system.

At present the alternating-current motor weighs somewhat more than the direct-current motor, and operates at a slightly lower efficiency. However, the smaller efficiency of the alternating-current motor is more than counterbalanced by the small

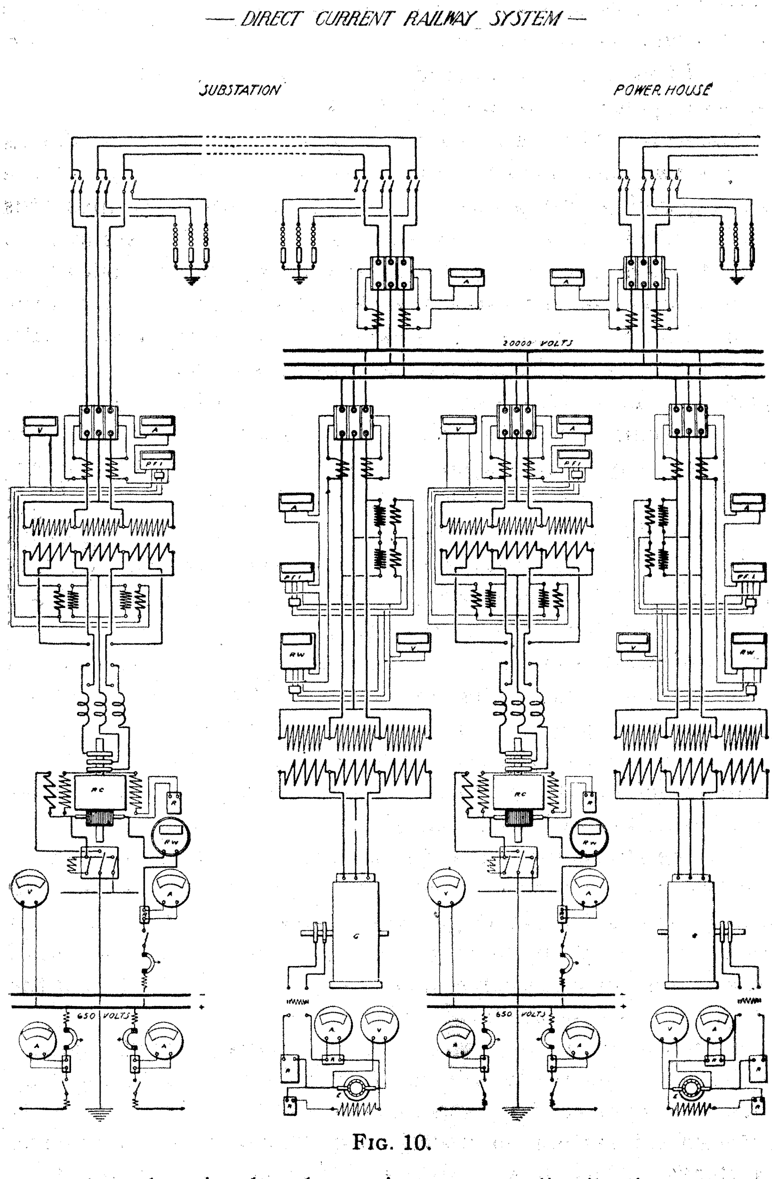


FIG. 10.

percentage loss in the alternating-current distributing system. And, furthermore, with the rapid development now taking place in the alternating-current motor, it is safe to assume that in the very near future its characteristics as to weight and efficiency will soon equal those of the direct-current motor, thus making the advantage of the alternating-current railway system still more evident.

An idea of the relative first cost for the two systems may be obtained by arranging in parallel columns the cost of the various items; this is done in the accompanying table and diagram. It is not necessary to take up in detail all the items, as they speak for themselves, but it may be of interest to note some items in which the costs vary more widely:

The single-phase generators, as would be expected, cost nearly 30% more than three-phase generators, this increase in cost amounts to $5000. Small savings on switchboard and wiring reduce the total for the power-house $3500 in favor of the direct-current system.

For the sub-station in the power-house, principally on account of saving in converter and transformer capacity, the balance is $8000 in favor of the alternating-current system.

The transmission systems are approximately the same, there being $2000 in favor of the alternating-current system.

In the alternating-current distributing system, while the suspension of the trolley is noticeably more expensive than in the direct-current system, on account of special insulators, the immense saving in copper gives a balance of $78 000 in favor of the alternating-current system.

The necessity of bonding only one rail effects a saving of $16 000, in favor of the alternating-current system.

A very liberal allowance has been made by placing the cost of the alternating-current motor equipments one third in excess of that of the direct-current motor equipments; this, as above noted, is the present cost of the alternating-current equipment, and without doubt in the near future this difference will be greatly reduced.

The total investment for the direct-current system under the assumed conditions is $490 100, while that of the alternating-current system is $371 600. Reducing this to the cost per mile, it is found that the electrical equipment complete amounts to $8168 for the direct-current system, and $6193 for the alternating-current system, or a saving of $1955 per mile in favor of the alternating-current system. Expressed in percentage, this means that the alternating-current system effects a saving of 25% of the cost of the direct-current system; in other words, the cost of the direct-current system is 32% more than the cost of the alternating-current system, a showing

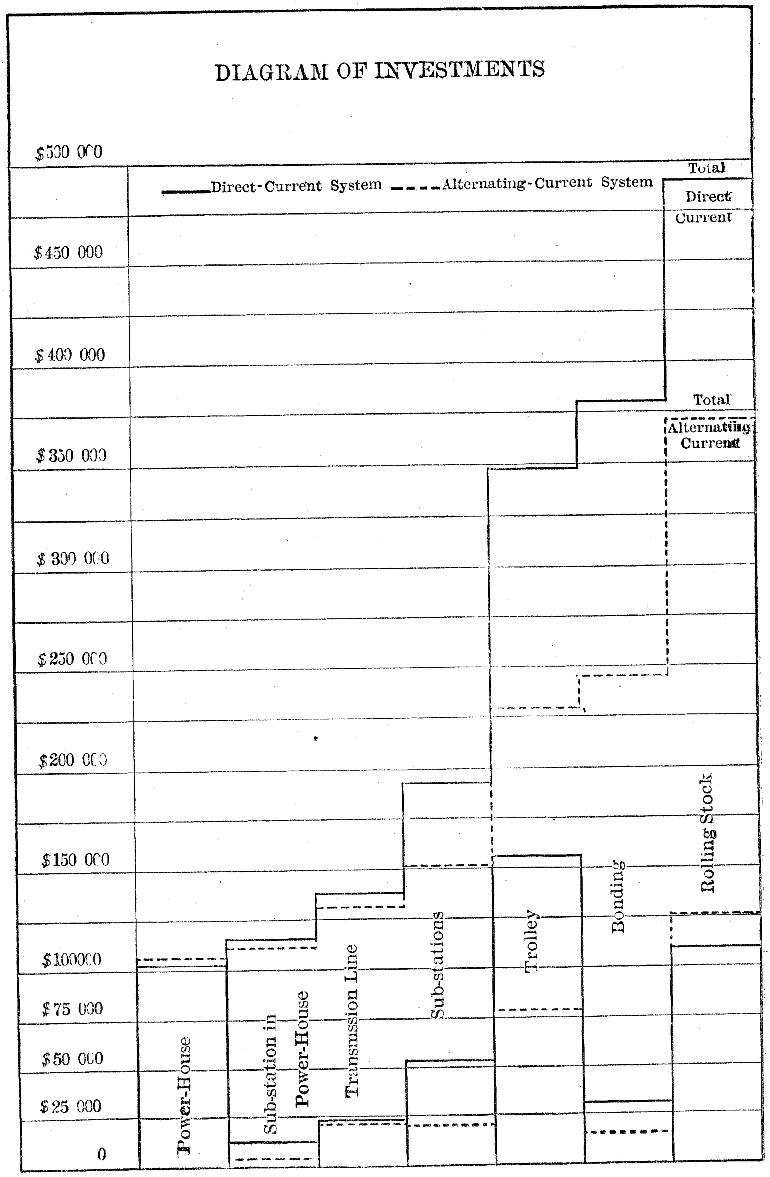


FIG. 11.

most favorable for the latter, and this indeed during the first year that this apparatus has been on the market.

With the alternating-current motor thus far perfected and the large number of propositions whose realization is conditioned by a cheaper electrical equipment, it looks as if the alternating-current system would be very widely adopted.

ESTIMATED COST OF THE ELECTRICAL EQUIPMENT OF A 60-MILE, SINGLE-TRACK INTERURBAN RAILWAY.

POWER-HOUSE.	*Direct-Current System.*	*Alternating-Current System.*
Building	$10 000	$10 000
Foundations	2 500	2 500
Boilers and settings	12 000	12 000
Steam piping and covering	7 500	7 500
Engines	22 000	22 000
Generators: two 400-kw	18 000	23 000
Exciters	1 000	1 000
Step-up transformers, 800-kw	8 000	7 500
Switchboard	3 500	3 000
Wiring	3 000	2 500
Feed-water heater	800	800
Pumps	800	800
Coal storage	1 000	1 000
Smoke-stack and flues	2 000	2 000
Fuel economizers	3 000	3 000
Stokers	3 500	3 500
Incidentals	4 400	4 400
Totals	$103 000	$106 500

SUB-STATION IN POWER-HOUSE.	*Direct-Current.*	*Alternating-Current.*
Building extension	$1 000	$600
Synchronous converter, 300-kw	4 800	
Transformer, 300-kw.; 200-kw. alternating current	3 200	2 000
Switchboard	2 000	1 300
Wiring	1 000	500
Incidentals	600	200
Total	$12 600	$4 600

48-MILE TRANSMISSION LINE.	*Direct-Current.*	*Alternating-Current.*
Poles charged to trolley line		
Copper	$10 000	$11 500
Insulators, pins and cross-arms	7 500	5 000
Erection	4 000	3 000
Incidentals	1 000	1 000
Total	$22 500	$20 500

SUB-STATION ALONG THE ROAD.	*Direct-Current.*	*Alternating-Current.*
Building	$2 000	$1 000
Synchronous converter	4 800	
Step-down transformers	3 200	2 000
Switchboard	2 000	1 300
Wiring	1 000	500
Incidentals	500	200
Total	$13 500	$5 000
Four sub-stations	$54 000	$20 000

TROLLEY-LINE AND FEEDERS	*Direct-Current System.*	*Alternating-Current System.*
Poles, 3500	$17 500	$17 500
Poles distributed and set	4 000	4 000
Guys and anchors	2 000	2 CCO
Brackets with hangers	18 000	25 000
Copper, direct current:		
Feeder 12 miles, 500 000 cir. mils		
" 48 " No. 0000		
Trolley, 120 " No. 000	95 000	
Alternating current:		
Trolley, 60 miles, No. 00		21 500
Feeder insulators	2 000	
Erection	10 000	4 000
Incidentals	7 500	4 000
Total	$156 000	$78 000

BONDING OF RAILS.	*Direct-Current.*	*Alternating-Current.*
Both rails bonded	$30 000	
One rail bonded		$15 000
Cross bonds	2 000	1 0C0
Total	$32 000	$16 C00

ROLLING STOCK.	*Direct-Current.*	*Alternating-Current.*
10 vestibuled passenger-cars, each equipped with 4 motors, and weighing about 30 tons	$75 000	$85 000
2 express passenger-cars, equipped with 4 motors and weighing about 35 tons	18 000	20 500
2 Baggage-cars, each equipped with 4 motors and weighing about 30 tons	:0 000	:2 000
Snow-plow and construction-car	7 000	8 500
Total	$110 000	$126 000

RECAPITULATION.	*Direct-Current.*	*Alternating-Current.*
Power-house	$103 000	$106 500
Sub-station in power-house	12 600	4 600
Transmission line	22 500	20 500
Sub-stations	54 000	20 000
Trolley-line and feeders	156 000	78 0C0
Bonding	32 000	16 CC0
Rolling stock	110 000	126 C00
Total	$490 100	$371 600

Cost per mile, direct-current system......$490 100/60 = $8 168
" " alternating-current system.... 371 600/60 = 6 193

Saving per mile, alternating-current system.... $1 955

The decrease of alternating-current cost in terms of direct-current investment, 25%.

The increase of direct-current cost in terms of alternating-current investment, 32%.